Chapter 4

Effects of Media

Objectives: When you have completed this chapter, you will be able to describe several important variables in the media through which the radiation passes and how they affect the particles/waves arriving at the telescope. You will be able to describe atmospheric "windows" and give an example. You will be able to describe the effects of absorbing and dispersing media on wave propagation. You will be able to describe Kirchhoff's laws of spectral analysis, and give examples of sources of spectral lines. You will be able to define reflection, refraction, scintillation, and Faraday rotation.

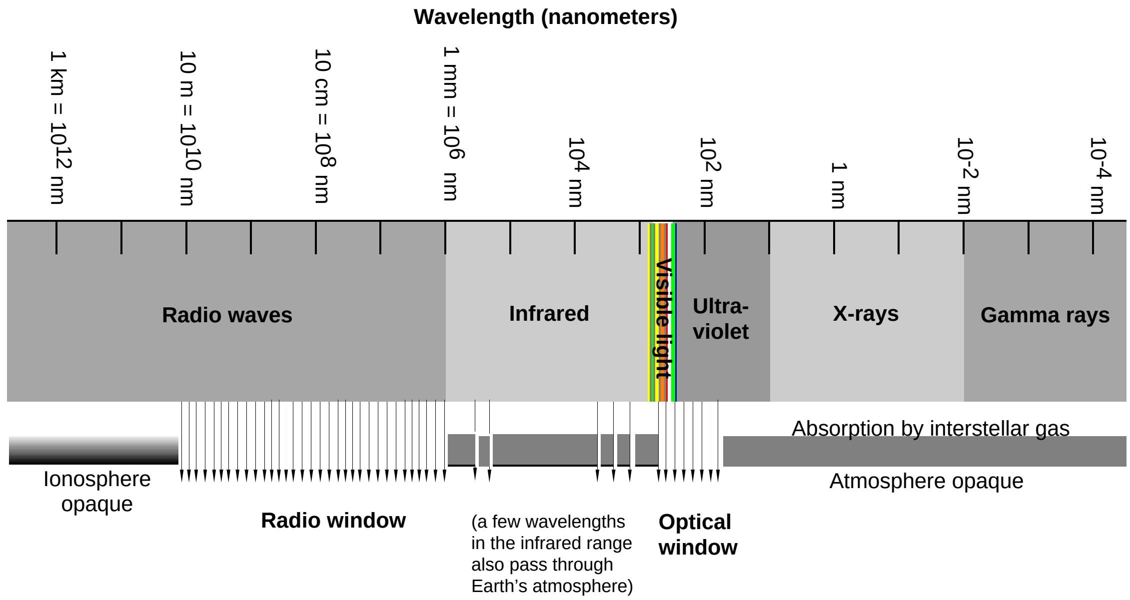
Electromagnetic radiation from space comes in all the wavelengths of the spectrum, from gamma rays to radio waves. However, the radiation that actually reaches us is greatly affected by the media through which it has passed. The atoms and molecules of the medium may absorb some wavelengths, scatter (reflect) other wavelengths, and let some pass through only slightly bent (refracted).

Atmospheric "Windows"

Earth's atmosphere presents an opaque barrier to much of the electromagnetic spectrum. The atmosphere absorbs most of the wavelengths shorter than ultraviolet, most of the wavelengths between infrared and microwaves, and most of the longest radio waves. That leaves only visible light, some ultraviolet and infrared, and short wave radio to penetrate the atmosphere and bring information about the universe to our Earth-bound eyes and instruments.

The main frequency ranges allowed to pass through the atmosphere are referred to as the radio window and the optical window. The radio window is the range of frequencies from about 5 MHz to over 300 GHz (wavelengths of almost 100 m down to about 1 mm). The low-frequency end of the window is limited by signal absorption in the ionosphere, while the upper limit is determined by signal attenuation caused by water vapor and carbon dioxide in the atmosphere.

Atmospheric Windows to Electromagnetic Radiation



The optical window, and thus optical astronomy, can be severely limited by atmospheric conditions such as clouds and air pollution, as well as by interference from artificial light and the literally blinding interference from the sun's light. Radio astronomy is not hampered by most of these conditions. For one thing, it can proceed even in broad daylight. However, at the higher frequencies in the atmospheric radio window, clouds and rain can cause signal attenuation. For this reason, radio telescopes used for studying sub-millimeter wavelengths are built on the highest mountains, where the atmosphere has had the least chance for attenuation. (Conversely, most radio telescopes are built in low places to alleviate problems with human-generated interference, as will be explained in Chapter 6.)

Absorption and Emission Lines

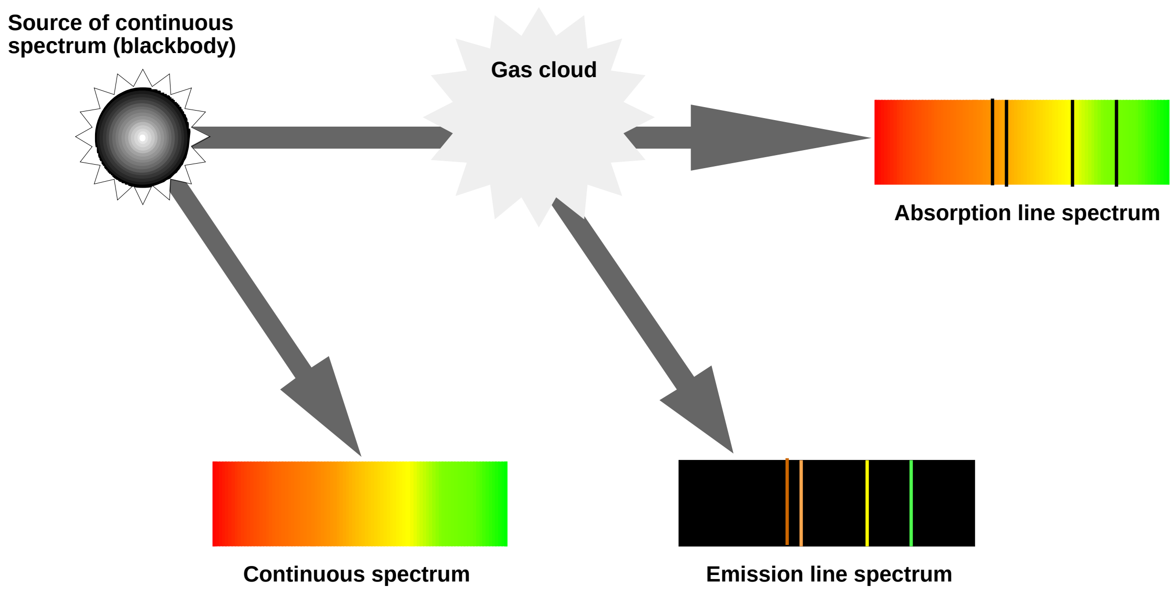
As described in Chapter 3, a blackbody object emits radiation of all wavelengths. However, when the radiation passes through a gas, some of the electrons in the atoms and molecules of the gas absorb some of the energy passing through. The particular wavelengths of energy absorbed are unique to the type of atom or molecule. The radiation emerging from the gas cloud will thus be missing those specific wavelengths, producing a spectrum with dark absorption lines.

The atoms or molecules in the gas then re-emit energy at those same wavelengths. If we can observe this re-emitted energy with little or no back lighting (for example, when we look at clouds of gas in the space between the stars), we will see bright emission lines against a dark background. The emission lines are at the exact frequencies of the absorption lines for a given gas. These phenomena are known as Kirchhoff's laws of spectral analysis:

1. When a continuous spectrum is viewed through some cool gas, dark spectral lines (called absorption lines) appear in the continuous spectrum.

2. If the gas is viewed at an angle away from the source of the continuous spectrum, a pattern of bright spectral lines (called emission lines) is seen against an otherwise dark background.

Kirchhoff's Laws of Spectral Analysis



The same phenomena are at work in the non-visible portions of the spectrum, including the radio range. As the radiation passes through a gas, certain wavelengths are absorbed. Those same wavelengths appear in emission when the gas is observed at an angle with respect to the radiation source.

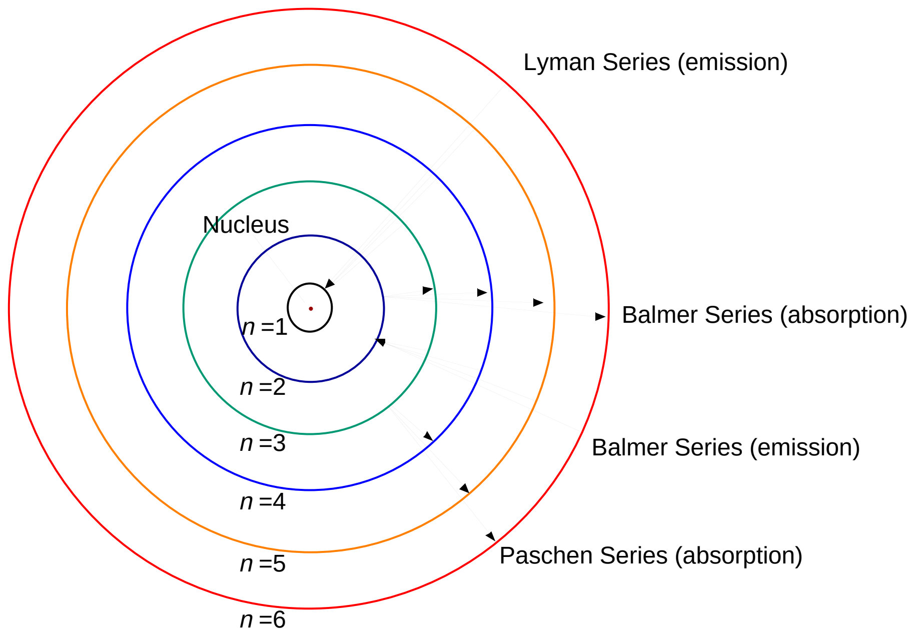
Why do atoms absorb only electromagnetic energy of a particular wavelength? And why do they emit only energy of these same wavelengths? What follows here is a summarized explanation, but for a more comprehensive one, see Kaufmann's *Universe*, pages 90-96.

The answers lie in quantum mechanics. The electrons in an atom may be in a number of allowed energy states. In the atom's ground state, the electrons are in their lowest energy states. In order to jump to one of a limited number of allowed higher energy levels, the atom must gain a very specific amount of energy. Conversely, when the electron "falls" to a lower energy state, it releases a very specific amount of energy. These discrete packets of energy are called photons.

Thus, each spectral line corresponds to one particular transition between energy states of the atoms of a particular element. An absorption line occurs when an electron jumps from a lower energy state to a higher energy state, extracting the required photon from an outside source of energy such as the continuous spectrum of a hot, glowing object. An emission line is formed when the electron falls back to a lower energy state, releasing a photon.

The diagram on the next page demonstrates absorption and emission of photons by an atom using the Neils Bohr model of a hydrogen atom, where the varying energy levels of the electron are represented as varying orbits around the nucleus. (We know that this model is not literally true, but it is useful for describing electron behavior.) The varying series of absorption and emission lines represent different ranges of wavelengths on the continuous spectrum. The Lyman series, for example, includes absorption and emission lines in the ultraviolet part of the spectrum.

Hydrogen Atom
(with allowed electron energy levels n = 1, 2, 3, etc.)



Emission and absorption lines are also seen when oppositely charged ions recombine to an electrically neutral state. The thus formed neutral atom is highly excited, with electrons transitioning between states, emitting and absorbing photons. The resulting emission and absorption lines are called recombination lines. Some recombination lines occur at relatively low frequencies, well within the radio range, specifically those of carbon ions.

Molecules, as well as atoms, in their gas phase also absorb characteristic narrow frequency bands of radiation passed through them. In the microwave and long wavelength infrared portions of the spectrum, these lines are due to quantized rotational motion of the molecule. The precise frequencies of these absorption lines can be used to determine molecular species. This method is valuable for detecting molecules in our atmosphere, in the atmospheres of other planets, and in the interstellar medium. Organic molecules (that is, those containing carbon) have been detected in space in great abundance using molecular spectroscopy. Molecular spectroscopy has become an extremely important area of investigation in radio astronomy.

As will be discussed in Chapter 5, emission and absorption lines in all spectra of extraterrestrial origin may be shifted either toward higher (blue) or lower (red) frequencies, due to a variety of mechanisms.

Recap

1. Earth's atmospheric radio window allows frequencies of about _______ to _________ to pass through.
2. When a continuous spectrum is viewed through a cool gas, dark _____________ _________________ appear in the spectrum.
3. Each spectral line corresponds to one particular ______________ between energy states of particular atoms or molecules.
4. The method of identifying molecules in atmospheres by observing their absorption lines is called _______________ _______________.
5. _______________ lines occur when oppositely charged ions recombine to a neutral, yet highly excited state.

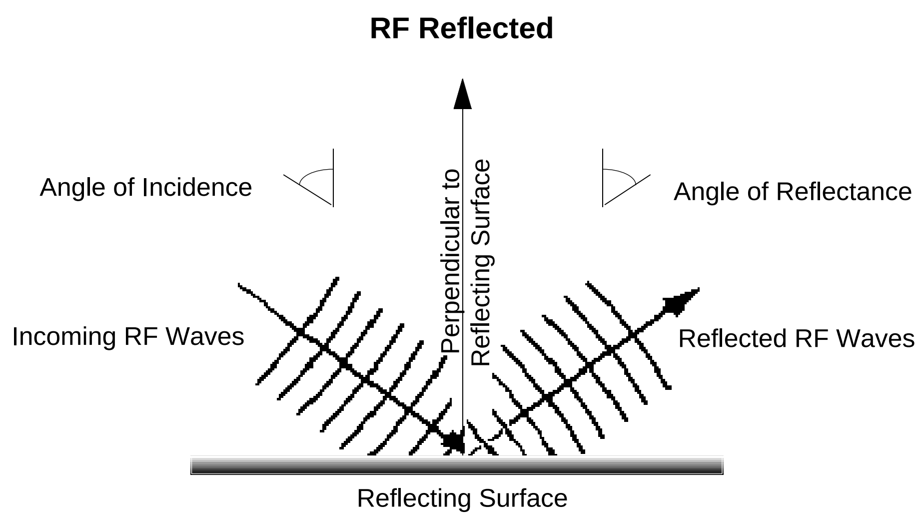
1. 5 MHz, 300 GHz   2. absorption lines   3. transition   4. molecular spectroscopy   5. Recombination

For Further Study

- *Atmospheric windows:* Kaufmann, 116-117; Wynn-Williams, 13-15; Morrison et al., 141, 169-172.
- *Spectral lines:* Kaufmann, 90-96; Wynn-Williams, 18-27.

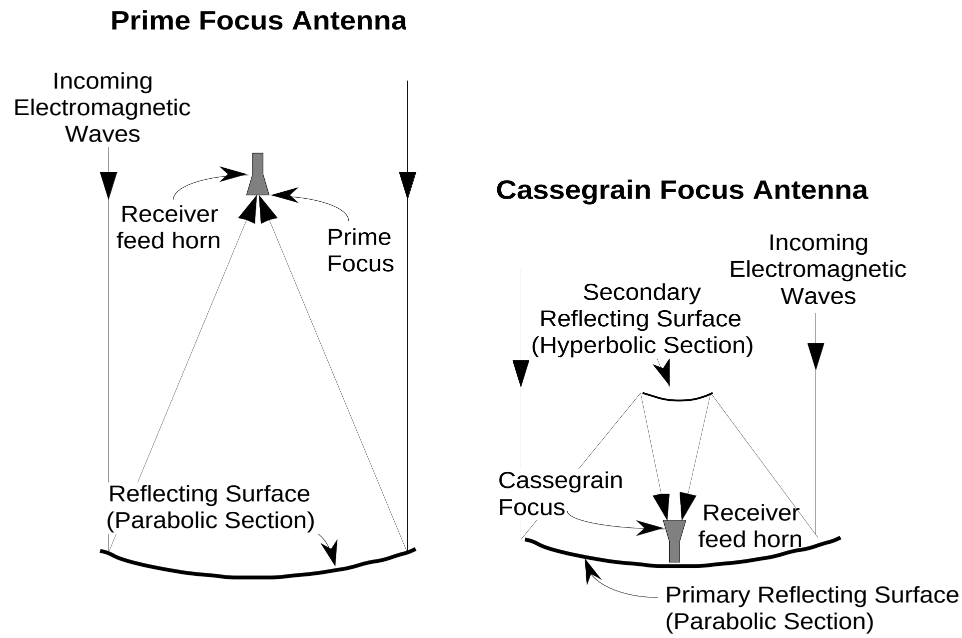
Reflection

RF radiation generally travels through space in a straight line. RF waves can be reflected by certain substances, much in the same way that light is reflected by a mirror. The angle at which a radio wave is reflected from a smooth metal surface, for example, will equal the angle at which it approached the surface. In other words, the angle of reflection of RF waves equals their angle of incidence.



This principle of RF reflection is used in antenna design to focus transmitted waves into a narrow beam and to collect and concentrate received RF signals for a receiver. If a reflector is designed with the reflecting surface shaped like a paraboloid, electromagnetic waves approaching parallel to the axis of the antenna will be reflected and will focus above the surface of the reflector at the feed horn. This arrangement is called prime focus and provides the large aperture (that is, antenna surface area) necessary to receive very weak signals.

However, a major problem with prime focus arrangements for large aperture antennas is that the equipment required at the prime focus is heavy and the supporting structure tends to sag under the weight of the equipment, thus affecting calibration. A solution is the Cassegrain focus arrangement. Cassegrain antennas add a secondary reflecting surface to “fold” the electromagnetic waves back to a prime focus near the primary reflector. The DSN’s antennas (including the GAVRT) are of this design because it accommodates large apertures and is structurally strong, allowing bulky equipment to be located nearer the structure’s center of gravity.

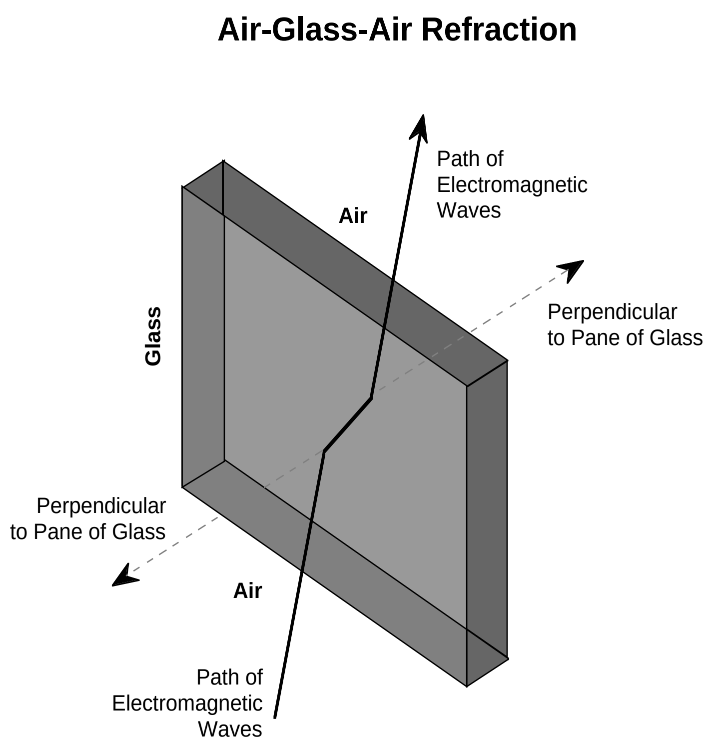


The reflective properties of electromagnetic waves have also been used to investigate the planets using a technique called planetary radar. With this technique, electromagnetic waves are transmitted to the planet, where they reflect off the surface of the planet and are received at one or more Earth receiving stations. Using very sophisticated signal processing techniques, the receiving stations dissect and analyze the signal in terms of time, amplitude, phase, and frequency. JPL's application of this radar technique, called Goldstone Solar System Radar (GSSR), has been used to develop detailed images and measurements of several main belt and near-Earth asteroids.

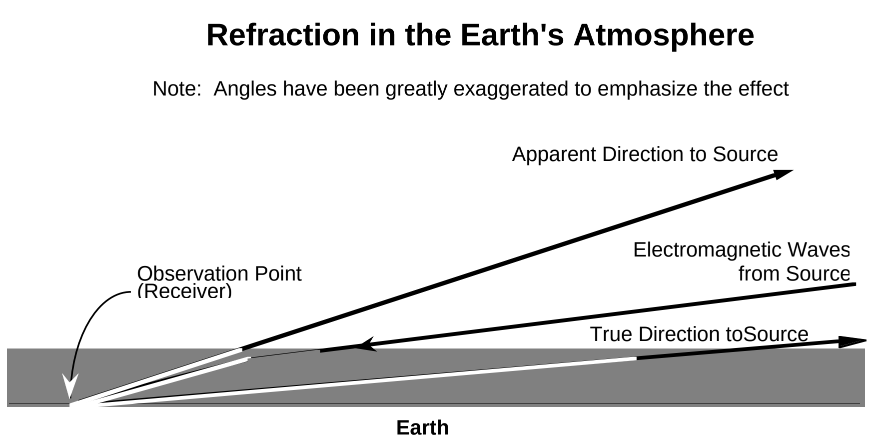
Refraction

Refraction is the deflection or bending of electromagnetic waves when they pass from one kind of transparent medium into another. The index of refraction is the ratio of the speed of electromagnetic energy in a vacuum to the speed of electromagnetic energy in the observed medium. The law of refraction states that electromagnetic waves passing from one medium into another (of a differing index of refraction) will be bent in their direction of travel.

Usually, substances of higher densities have higher indices of refraction. The index of refraction of a vacuum, by definition, is 1.0. The index of refraction of air is 1.00029, water is 1.3, glass about 1.5, and diamonds 2.4. Since air and glass have different indices of refraction, the path of electromagnetic waves moving from air to glass at an angle will be bent toward the perpendicular as they travel into the glass. Likewise, the path will be bent to the same extent away from the perpendicular when they exit the other side of glass.



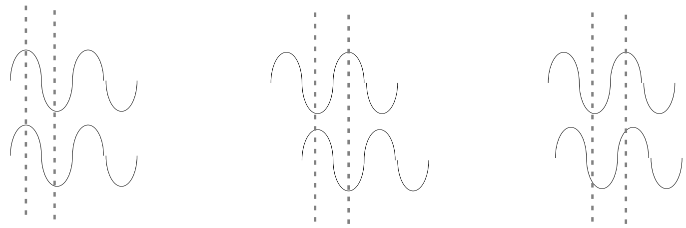
In a similar manner, electromagnetic waves entering Earth's atmosphere from space are slightly bent by refraction. Atmospheric refraction is greatest for radiation from sources near the horizon (below about 15˚ elevation) and causes the apparent altitude of the source to be higher than the true height. As Earth rotates and the object gains altitude, the refraction effect decreases, becoming zero at zenith (directly overhead). Refraction's effect on sunlight adds about 5 minutes to the daylight at equatorial latitudes, since the sun appears higher in the sky than it actually is.



Phase

As applied to waves of electromagnetic radiation, phase is the relative measure of the alignment of two wave forms of similar frequency. They are said to be in phase if the peaks and troughs of the two waves match up with each other in time. They are said to be out of phase to the extent that they do not match up. Phase is expressed in degrees from 0 to 360.

Phase



Scintillation

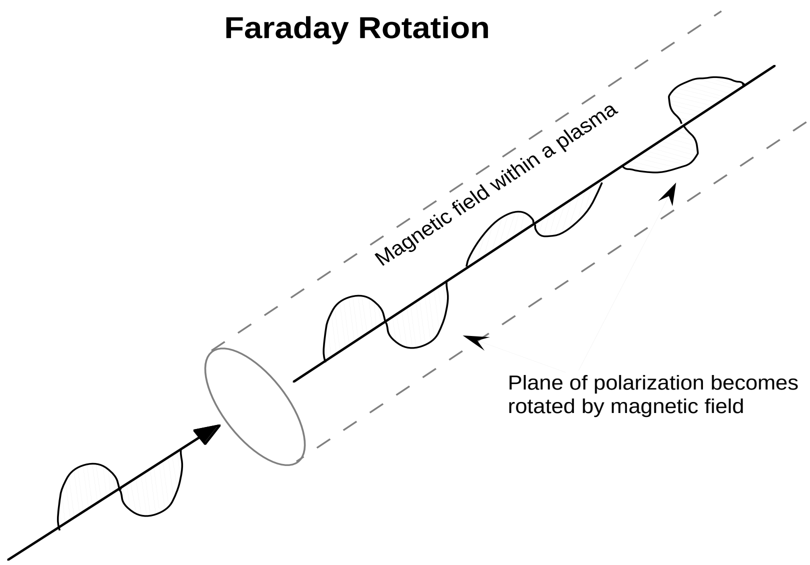
As electromagnetic waves travel through Earth's atmosphere, they pass through areas of varying pressure, temperature, and water content. This dynamic medium has rapidly varying indices of refraction, causing the waves to take different paths through the atmosphere. The consequence is that at the point of observation, the waves will be out of phase and appear to be varying in intensity. The effect in the visual range is that stars appear to twinkle and distant scenes on the horizon appear to shimmer (for example, when we see distant "water" mirages in the hot desert). In the radio range, the same phenomenon is called scintillation. The interplanetary and interstellar media can have a similar effect on the electromagnetic waves passing through them.

A star will scintillate or twinkle most violently when it is low over the horizon, as its radiation passes through a thick layer of atmosphere. A planet, which appears as a small disk, rather than a point, will usually scintillate much less than a star, because light waves from one side of the disk are "averaged" with light waves coming from other parts of the disk to smooth out the overall image.

Technology has been developed for both radio and optical telescopes to significantly cancel out the phase changes observed for a given source, thus correcting the resulting distortion. This technology is not implemented on the GAVRT.

Faraday Rotation

Faraday rotation (or Faraday effect) is a rotating of the plane of polarization of the linearly polarized electromagnetic waves as they pass through a magnetic field in a plasma. A linearly polarized wave may be thought of as the sum of two circularly polarized waves of opposite hand. That is, one wave is polarized to the right and one wave is polarized to the left. (Both waves are at the same frequency.) When the linearly polarized wave passes through a magnetic field, the right polarized wave component travels very slightly faster than the left polarized wave component. Over a distance, this phenomenon has the effect of rotating the plane of the linearly polarized wave. A measure of the amount of rotation can give a value of the density of a plasma.



Recap

1. The angle of reflectance of electromagnetic radiation from a surface is equal to the angle of __________________.

2. For a radio telescope, Earth's atmosphere causes refraction of the radiation from a source such that the source appears (higher/lower) ____________ than it really is.

3. The ratio of the speed of electromagnetic energy in a vacuum to its speed in a given medium is the medium's ____________ ____ ________________.

4. Scintillation is caused by electromagnetic waves being out of _________ after passing through a dynamic medium.

5. Faraday rotation occurs when an electromagnetic wave's _______________ is changed as it passes through magnetic lines of force parallel to the wave and moving in the same direction.

1. incidence   2. higher   3. index of refraction   4. phase   5. polarization

For Further Study

- *Reflection, refraction, and telescope design:* Kaufmann, 102-116; Morrison et al., 140-147, 150-158, 161-178.
- *Radio metrics:* http://deepspace.jpl.nasa.gov/920/public/923tech/95_20/radio.htm; Morrison et al., 95-96, 167-168, 187-188.
- *Faraday rotation:* Wynn-Williams, 108-110.